

# The dominant X-ray wind in massive star binaries

J.M. Pittard<sup>1</sup> and I.R. Stevens<sup>2</sup>

<sup>1</sup> Department of Physics & Astronomy, The University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK

<sup>2</sup> Department of Physics & Astronomy, The University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

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**Abstract.** We investigate which shocked wind is responsible for the majority of the X-ray emission in colliding wind binaries, an issue where there is some confusion in the literature, and which we show is more complicated than has been assumed. We find that where both winds rapidly cool (typically close binaries), the ratio of the wind speeds is often more important than the momentum ratio, because it controls the energy flux ratio, and the *faster* wind is generally the dominant emitter. When both winds are largely adiabatic (typically long-period binaries), the slower and denser wind will cool faster and the *stronger* wind generally dominates the X-ray luminosity.

**Key words.** stars:binaries:general – stars:early-type – stars:Wolf-Rayet – X-rays:stars

## 1. Introduction

The violent wind-wind collision in massive star binaries creates a region of high temperature shock-heated plasma, which can contribute to the total system emission at radio, infrared, optical, ultraviolet and X-ray wavelengths. Over the last 20 years, theoretical models have focussed mainly on the dynamics of the stellar winds and the wind collision zone (WCZ), and on the resulting X-ray emission (Pittard 2000 and references therein). As the X-ray emission is dependent on the physical conditions within the WCZ and on the distribution and properties of the unshocked attenuating wind material, observations provide information on basic parameters of the system (see Stevens et al. 1996; Zhekov & Skinner 2000; Pittard & Corcoran 2002).

To interpret such observations, it is useful to know which wind dominates the X-ray emission. For instance, if there is a velocity difference between the winds, we would like to be able to predict how hot the broad-band emission will be, or if there are abundance differences, how strong or weak certain lines will be (this is of particular relevance now that grating observations can resolve line profiles).

Simple expressions for the X-ray luminosity from each of the shocked winds were presented in a complex, yet elegant paper, which provides some answers to these questions in terms of fundamental parameters of the system (Usov 1992). Their applicability has resulted in their common use in the literature and in observing proposals. However, we have recently discovered inconsistencies be-

tween results from these expressions and those determined from numerical models, leading to some confusion on the issue of the dominant X-ray emitting wind. In this letter we reinvestigate previous conclusions in the literature.

## 2. Estimates of $L_1/L_2$

Let us define  $L_1$  as the X-ray luminosity from the shocked wind with the greater momentum flux (i.e. the ‘stronger’ wind), and  $L_2$  the equivalent from the shocked weaker wind. Analytical estimates in the literature of the ratio of  $L_1/L_2$  exist for two limiting cases: the radiative limit, where the cooling timescale for the hot gas from both winds is assumed small in comparison to the timescale for flow of this gas out of the system (i.e.  $\chi < 1$ , see Sec. 2.2); and the adiabatic limit, where the opposite is true. We will first focus on these limiting cases, before discussing the behaviour of  $L_1/L_2$  between these limits.

### 2.1. $L_1/L_2$ in the radiative limit

In this limit, the entire kinetic energy thermalized by the shocks is immediately radiated (normally with the majority at X-ray energies), and the region of shocked gas is thin. Binary systems with a small orbital separation are favoured, and examples near this limit include V444 Cyg (WN5 + O6;  $P = 4.2$  d; Corcoran et al. 1996) and DH Cep (O5.5-6V + O6.5-7V;  $P = 2.11$  d; Penny et al. 1997).

Let us first consider the region of the WCZ which lies directly between the stars. As there is a momentum balance, the relative kinetic energy fluxes are proportional to the ratio of the wind speeds, so emission from this volume should be dominated by gas from the star with the

faster wind. If, for simplicity, we initially assume that the pre-shock wind speeds are spatially invariant, we find that the majority of the thermalized energy in the WCZ occurs close to the line of centres (see Fig. 1). Under these conditions, the faster wind dominates the *total* emission.

If the pre-shock wind speeds are approximately equal, neither star should significantly dominate the total emission. In such circumstances, one might expect secondary considerations, such as the wind momentum ratio, to become important. Luo et al. (1990) noted that if  $v_1 \approx v_2$ , the weaker wind should be more luminous, based on the premise that it has, on average, a larger velocity component normal to the shock front: referring to V444 Cyg they argue that, “Because of this, the shocked O6 wind dominates the X-ray emission from the shocked region”. However, we show below that even for very large wind momentum ratios, the stronger wind still accounts for almost half of the total emission. Therefore Luo et al.’s use of the word “dominates” goes too far, although their basic conclusion that the O6 wind is the majority emitter is consistent with our analysis. Complicating factors, such as wind acceleration, are discussed later.

We can obtain analytical estimates for  $L_1/L_2$  from the relevant equations in Usov (1992). For the radiative limit, the total X-ray luminosity from the external wind shock is (cf. his Eq. 88)  $L_1 = 2.3 \rho_\infty v_1^3 z_{\text{OB}}^2$ , where  $\rho_\infty = \dot{M}_1/4\pi D^2 v_1$ ,  $z_{\text{OB}}$  is the distance of the contact discontinuity from the centre of the star with the weaker wind ( $= \sqrt{\eta}D/(1 + \sqrt{\eta})$ ),  $D$  is the stellar separation, and  $\eta$  is the momentum ratio of the winds ( $= \dot{M}_2 v_2 / \dot{M}_1 v_1$ ). Usov (1992) parameterizes the luminosity from the internal wind shock as  $L_2 = 0.22 \dot{M}_2 v_2^2$ .

With the same parameter values as used by Luo et al. (1990) for V444 Cyg, these equations yield  $L_1/L_2 = 0.59$  (i.e. that the weaker wind is the dominant X-ray emitter), in agreement with the statement in Luo et al. (1990). From Usov (1992) we find that  $L_1/L_2 \propto \dot{M}_1 v_1^3 / \dot{M}_2 v_2^2 \approx \rho_1 v_1^3 / \rho_2 v_2^3$ , which at the stagnation point is proportional to  $v_1/v_2$ , such that as expected the faster wind will normally be the dominant X-ray emitter. While this agreement is satisfying, an indication of potential problems with the equations in Usov (1992) is revealed by considering the predicted value of  $L_1/L_2$  for identical winds: in this case we obtain  $L_1/L_2 = 0.2$ , instead of unity!

We have therefore performed a numerical calculation of the kinetic energy flux normal to the wind shocks to precisely determine  $L_1/L_2$  for various wind parameters. The position of the contact discontinuity (which is also the position of the wind shocks since the wind collision region is thin) was obtained from integration of Eq. 4 in Stevens et al. (1992). We find that the value of  $L_1/L_2$  primarily depends on the ratio of the wind speeds and to a much lesser extent on the wind momentum ratio. Results are shown in Fig. 1 and in Table 1, where we have defined  $\Xi$  to be the fractional wind kinetic power normal to the contact discontinuity i.e.  $L_1 = 0.5\Xi_1 \dot{M}_1 v_1^2$  for the stronger wind.

For  $\eta = (0.01, 0.1, 1.0)$ , we find that  $\Xi_1 = (0.0042, 0.033, 0.167)$  and  $\Xi_2 = (0.564, 0.403, 0.167)$  respectively (the latter values being the analytical limit of  $1/6$ ), consistent with the solid angle of the wind collision zone as viewed from the star with the stronger (weaker) wind decreasing (increasing) with decreasing  $\eta$ . The ratio of Usov’s equations yield values for  $L_1/L_2$  which are too low in comparison to the exact numerical calculation by factors of (1.09, 1.74, 4.88) for  $\eta = (0.01, 0.1, 1)$  respectively, irrespective of the ratio of  $v_1/v_2$ . Thus Usov’s equations for the radiative limit are somewhat in error, being most accurate for low values of  $\eta$ .

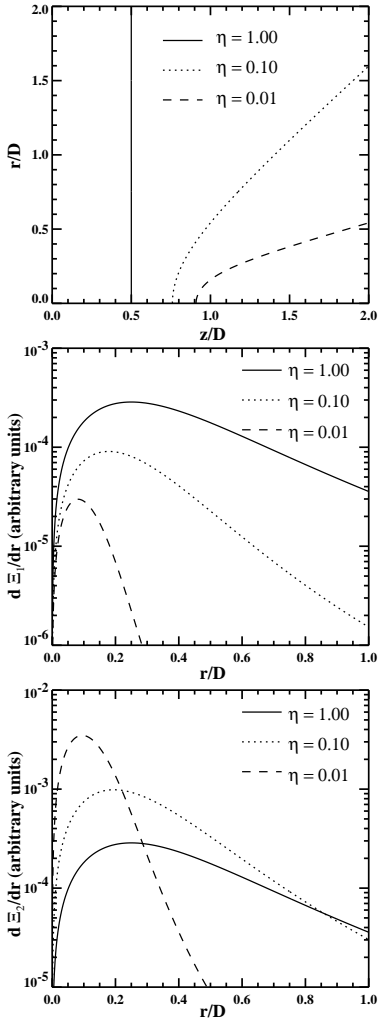
Fig. 1 also shows the gradient of  $\Xi$  as a function of the off-axis distance,  $r$ . In Table 2 we list the value of  $r$  at which  $\int_{r=0}^r (d\Xi/dr)dr$  is 50% and 90% of the asymptotic value of  $\Xi$ . For equal strength winds, 50% and 90% of the maximum wind kinetic power thermalized by the shocks (and hence radiated) occurs within  $r/D = 0.38$  and 0.95 (this off-axis distance is much smaller than the corresponding value for adiabatic winds cf. Luo et al. 1990). Therefore distortion of the WCZ by orbital motion should not significantly alter our previous conclusions. We can also safely relax our assumption of spatially invariant wind speeds as we only need to consider this ratio between the stars.

Finally, for close binaries we should also consider the potential role of radiative acceleration, inhibition (Stevens & Pollock 1994) and braking (Gayley et al. 1997) of the winds on  $L_1/L_2$ . As already shown, the ratio of the wind speeds is the critical parameter in such systems, and it seems plausible to expect this to continue to be true in the presence of these 3 effects. In such binaries, it is probable that neither wind will have room to reach terminal speed. Since the stronger wind will have more room to accelerate, we would normally expect it to be faster, and to dominate the emission. However, if there is substantial radiative inhibition plus braking, this will cause the strong wind to be by far the slower and will likely shift the dominant energy generation back to the weaker wind.

## 2.2. $L_1/L_2$ in the adiabatic limit

In direct contrast to the radiative limit, colliding wind systems are most likely to be near the adiabatic limit if the stellar separation is large. Perhaps the best example of such a system is the Wolf-Rayet binary WR 140 (WC7 + O4V;  $P = 2900$  d; Williams et al. 1997). Luo et al. (1990) argue that for a WR+O system in the adiabatic limit “the shocked WR stellar wind dominates the X-ray emission.” Myasnikov & Zhekov (1993) arrive at a similar conclusion for their “standard system” which is also near this limit: “the whole of the luminosity is due entirely to the emission of the shocked gas of the WR wind”, being more than an order of magnitude greater than the emission from the weaker wind.<sup>1</sup>

<sup>1</sup> Although Myasnikov & Zhekov (1993) actually use different abundances for each wind, gas with typical WN abundances



**Fig. 1.** Results for a wind-wind collision in the radiative limit, with equal and spatially invariant pre-shock speeds. The top panel shows the position of the contact discontinuity as a function of wind momentum ratio,  $\eta$ . Star 1 is located at  $(r,z) = (0,0)$ , and star 2 at  $(r,z) = (0,1)$ . The middle and bottom panels show the value of  $d\Xi/dr$  (see text) as a function of  $r$  and  $\eta$  for the wind of star 1 and star 2 respectively. Note that the majority of the thermalized kinetic power of the winds occurs well within  $r = D$  (see also Table 2).

While the appropriate equations in Usov (1992) are known to be lower limits (due to the omission of line emission), the ratio of  $L_1/L_2$  should not be overly affected and can once again be calculated. Using the same values for the stellar wind parameters as Myasnikov & Zhekov (1993), Eqs. 89 and 95 in Usov (1992) yield  $L_1/L_2 = 1.36$ , indicating that neither wind is particularly dominant. This is clearly in disagreement with the published statements in Luo et al. (1990) and Myasnikov & Zhekov (1993).

has a similar emissivity as gas with solar abundances, such that this difference is unimportant to their findings.

**Table 1.** Ratio of the wind X-ray luminosities in the radiative limit assuming spatially invariant pre-shock wind speeds. The value of  $L_1/L_2$  primarily depends on the ratio of the wind speeds,  $v_1/v_2$ , and to a lesser degree on the wind momentum ratio,  $\eta$ . Also tabulated are the ratios of the mass-loss rates and the wind kinetic power.

| $v_1/v_2$ | $\eta$ | $M_1/M_2$ | $M_1 v_1^2 / M_2 v_2^2$ | $L_1/L_2$ |
|-----------|--------|-----------|-------------------------|-----------|
| 2.000     | 10.0   | 0.05      | 0.200                   | 2.43      |
|           | 1.00   | 0.50      | 2.000                   | 2.00      |
|           | 0.10   | 5.00      | 20.00                   | 1.64      |
|           | 0.01   | 50.0      | 200.0                   | 1.48      |
| 1.000     | 10.0   | 0.10      | 0.100                   | 1.22      |
|           | 1.00   | 1.00      | 1.000                   | 1.00      |
|           | 0.10   | 10.0      | 10.00                   | 0.82      |
|           | 0.01   | 100.      | 100.0                   | 0.74      |
| 0.500     | 10.0   | 0.20      | 0.050                   | 0.61      |
|           | 1.00   | 2.00      | 0.500                   | 0.50      |
|           | 0.10   | 20.0      | 5.000                   | 0.41      |
|           | 0.01   | 200.      | 50.00                   | 0.37      |
| 0.250     | 10.0   | 0.40      | 0.025                   | 0.30      |
|           | 1.00   | 4.00      | 0.250                   | 0.25      |
|           | 0.10   | 40.0      | 2.500                   | 0.21      |
|           | 0.01   | 400.      | 25.00                   | 0.19      |

**Table 2.** Values of the off-axis distance,  $r$ , at which  $\Xi_1$  and  $\Xi_2$  are 50% and 90% of their maximum value for various  $\eta$ , and assuming spatially invariant, equal speed winds.

| $\eta$ | 0.5 $\Xi_{1,max}$ | 0.9 $\Xi_{1,max}$ | 0.5 $\Xi_{2,max}$ | 0.9 $\Xi_{2,max}$ |
|--------|-------------------|-------------------|-------------------|-------------------|
| 1.00   | 0.38              | 0.95              | 0.38              | 0.95              |
| 0.10   | 0.25              | 0.54              | 0.27              | 0.62              |
| 0.01   | 0.10              | 0.19              | 0.11              | 0.22              |

To investigate this issue we have calculated the X-ray luminosity from numerical simulations of the WCZ near the adiabatic limit. Table 3 summarizes our findings for winds with equal, spatially invariant pre-shock speeds. The general trend is for  $L_1/L_2$  to increase with decreasing  $\eta$  (which is opposite to the radiative limit), and for this ratio to become very large for small  $\eta$ . We thus find agreement with the work of Luo et al. (1990) and Myasnikov & Zhekov (1993), and conclude that the appropriate equations in Usov (1992) are again somewhat in error.

The underlying reason for the trend shown in Table 3 concerns the ratio of the cooling timescale to the flow timescale in each of the winds. Stevens et al. (1992) noted that, near the local minimum in the cooling curve (which implies that the pre-shock velocity at the stagnation point is in the range  $900 \text{ km s}^{-1} \lesssim v \lesssim 3500 \text{ km s}^{-1}$ ), this ratio can be approximated as  $\chi \approx v_8^4 d_{12} / \dot{M}_{-7}$ , where  $v_8$  is the wind velocity in units of  $1000 \text{ km s}^{-1}$ ,  $d_{12}$  is the distance from the star to the contact discontinuity in units of  $10^{12} \text{ cm}$ , and  $\dot{M}_{-7}$  is the mass-loss rate of the star in units of  $10^{-7} M_\odot \text{ yr}^{-1}$ . The shocked wind is radiative when  $\chi < 1$ , and approaches the adiabatic limit when  $\chi \gg 1$ . If we ignore the dependence of  $\chi$  on  $d$  (i.e. if we

**Table 3.** Ratio of the wind X-ray luminosities as a function of wind momentum ratio,  $\eta$ , for colliding wind systems with equal, spatially invariant wind speeds, equal abundances, and near to the adiabatic limit.

| $\eta$ | $L_1/L_2$ |
|--------|-----------|
| 1.0000 | 1.0       |
| 0.3160 | 1.9       |
| 0.1000 | 3.9       |
| 0.0316 | 9         |
| 0.0100 | 24        |

were to assume that the relevant distance appropriate to the flow dynamics is the same for each wind), the ratio of this characteristic cooling parameter for the two winds is  $\chi_1/\chi_2 \sim \dot{M}_2 v_1^4 / \dot{M}_1 v_2^4$ .

For the results in Table 3 where  $v_1 = v_2$ ,  $\chi_1/\chi_2 \sim \dot{M}_2/\dot{M}_1 = \eta$ . Hence as the value of  $\eta$  decreases in Table 3, the stronger wind becomes more efficient at emitting X-rays relative to the weaker wind. This is consistent with the fact that although the post-shock density at the stagnation point is the same for both winds, its decline with off-axis distance is faster for the weaker wind (as observed also by Myasnikov & Zhekov 1993). We note also that within a given distance from the stagnation point, the volume occupied by the shocked stronger wind exceeds that occupied by the shocked weaker wind.

One might expect that  $L_1/L_2 \sim 1$  when  $\chi_1/\chi_2 = 1$ , irrespective of the value of  $\eta$ . Again ignoring the dependence of  $\chi$  on  $d$ , we find that  $\eta = (v_2/v_1)^5$  for  $\chi_1/\chi_2 = 1$ . Thus to obtain comparable luminosity from each shocked wind when  $\eta = 0.1$ , we require  $v_1 \sim 1.6 v_2$ . Since, in reality, mass-loss rates from early-type stars can vary by several orders of magnitude, whereas wind velocities lie typically within the range 1000 – 3000 km s<sup>-1</sup> (excluding LBV's), we expect most systems near the adiabatic limit will have a luminosity dominated by the stronger wind.

### 2.3. $L_1/L_2$ in-between these limits

Estimates of the luminosity ratio for systems where the shocked winds are in-between the limiting radiative and adiabatic cases must be done on a case-by-case basis. Somewhere in this region of parameter space, the wind which dominates the X-ray emission must switch over from the one with the faster pre-shock speed (radiative limit) to the one with the slower pre-shock speed (adiabatic limit). In contrast, situations where one wind is clearly radiative and the other is closer to being adiabatic will have their X-ray emission dominated by the former (e.g. in  $\gamma^2$  Velorum, where  $\chi_1 \ll 1$  and  $\chi_2 > 1$ , the X-ray emission is dominated by the shocked WR wind).

## 3. Summary

In this letter we have re-examined the issue of which wind is the dominant X-ray emitter in colliding wind binaries,

following the discovery of some confusion in the existing literature. Our work supports the earlier conclusions in Luo et al. (1990) and Myasnikov & Zhekov (1993), though is sometimes in disagreement with the relevant analytical equations in Usov (1992).

For systems near the radiative limit (typically short period binaries), we find that the primary influence on  $L_1/L_2$  is the ratio of the wind speeds,  $v_1/v_2$ , since it controls the energy flux ratio. For  $v_1 = v_2$ ,  $L_1 \approx L_2$  irrespective of the wind momentum ratio,  $\eta$ . When  $v_1 \neq v_2$ , the faster wind normally dominates the luminosity, although it is unlikely to do so by more than a factor of 5. The equations in Usov (1992) predict values for  $L_1/L_2$  which can be in error by up to a factor of 4.

For systems near the adiabatic limit (e.g. long-period, high eccentricity binaries at apastron), we confirm earlier findings that the stronger wind is typically the dominant X-ray emitter, often by an order of magnitude relative to the weaker wind. This is because the dominant driver of  $L_1/L_2$  is the ratio of  $\chi_1/\chi_2$ , so that the stronger wind can in general more easily radiatively cool. If we force  $\chi_1/\chi_2 \sim 1$ , we find that both shocked winds contribute roughly equally to the X-ray emission irrespective of the value of  $\eta$ . In contrast, the equations in Usov (1992) yield  $L_1 \sim L_2$  irrespective of the assumed wind parameters.

For systems in-between these limits, we anticipate that the dominant luminosity should generally switch from the faster wind (radiative limit) to the slower wind (adiabatic limit). Where one shocked wind is substantially closer to the radiative limit than that of the other, the X-ray emission will naturally be dominated by the former.

This work provides a basic understanding of the dominant factors controlling the luminosity ratio in colliding wind binaries. Detailed calculations are needed to further investigate the effects of wind acceleration/braking and different wind abundances.

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